Technical White Paper for SuperMIMO

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1 Overview

Having developed for twenty years, the digital subscriber line (DSL) technology has become the mainstream access technology in the telecommunications field. The DSL technology keeps developing to meet requirements for higher bandwidth, showing great marketing potential. The latest Vectored DSL technologies defined in the ITU-T Recommendation G 993.5 have the ability to cancel crosstalk between neighboring twisted-pairs and provide channel bandwidth of 100 Mbps based on VDSL2 using 30a bandplan.

By combining channel expansion, crosstalk cancellation and multi-pair bonding based on the Vectored DSL and MIMO DSL, the SuperMIMO technology dramatically increases the DSL access rate because of extra virtual channels and a near crosstalk-free environment. The laboratory test results show that SuperMIMO helps achieve a downstream rate of over 300 Mbps by using two twisted pairs and of 700 Mbps by using four twisted pairs. SuperMIMO prolongs the life of twisted pair cable by increasing the access bandwidth.

2 Technical Principles of SuperMIMO

2.1 Latest DSL Technology

Nowadays, the DSL technology can achieve a symmetrical rate of 100 Mbps by using a single twisted pair. As access scenarios evolve, digital subscriber line access multiplexers (DSLAMs) move out of center offices (COs) to curbs and buildings through fibers (FTTC/B), much closer to end users. Access lines therefore become shorter. When the distance from DSLAMs to end users are short （e.g. within 300 meters）, attenuation of signals on common twisted pairs is small and a wide frequency spectrum is available. As a result, there is a probability for high-rate access, and this is one of the main advantages for bringing fiber closer to the end users.

Requirements for higher access bandwidth, however, will increase more rapidly. According to the Nielsen law, five years later, requirements for the mainstream access bandwidth will be higher than that very-high-speed digital subscriber Line 2 (VDSL2) can provide. However, copper cables will still be commonly used for access because the cost of fiber deployment is high and some areas are not suitable for fiber deployment for a long time, which continuously requires increase of the access bandwidth of copper cables.

Multi-pair bonding may partially solve the preceding problem. If there is no crosstalk, multi-pair bonding defined in ITU-T Recommendation G.998.x series can multiple access bandwidth or extends the coverage. Standards for multi-pair bonding have been published over years and therefore this technology is quite mature. However, multi-pair bonding still has its disadvantage, the major one of which is, the crosstalk between twisted pairs [3], [5] and [6]. Because of the crosstalk, the actual total rate provided by multi-pair bonding is much less than the theoretical rate.

Vectoring is developed to mitigate crosstalk on DSL. Vectoring cancels crosstalk by means of pre-coding signals in the downstream direction and coordinated reception of signals in the upstream direction at DSLAMs. In this way, crosstalk is almost canceled if the amplitude of the crosstalk signals is relatively smaller than that of the native signals in the channel, which is typically true. Vectoring is a single-end crosstalk cancellation technology at the DSLAM side because signals received by users on the customer premises equipment (CPE) side cannot be jointly processed. ITU-T Recommendation G.993.5 defining vectoring was consented by ITU-T Study Group (SG) 15 in April, 2010.

According to ITU-T Recommendation G 993.5, the use of vectoring over bonded lines is defined as bonded vectoring or as multiple input multiple output (MIMO) DSL, a technology that provides higher access bandwidth than multi-pair bonding does. Compared with multi-pair bonding DSL, MIMO DSL increases the bandwidth by 50 percent to 100 percent depending on the intensity of crosstalk. The greater the crosstalk is, the greater the gains are obtained by crosstalk cancellation.

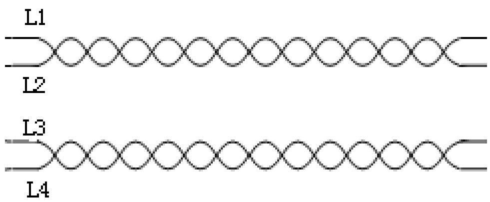
SuperMIMO may further increase the access bandwidth that MIMO DSL can provide, bringing out the potential of copper cables amazingly. For example, SuperMIMO using four twisted pairs can achieve a downstream rate of 700 Mbps at a distance of 400 meters, dramatically increasing MIMO DSL bandwidth by 75 percent.

2.2 Technical Principles of SuperMIMO

1. Construct expanded channels

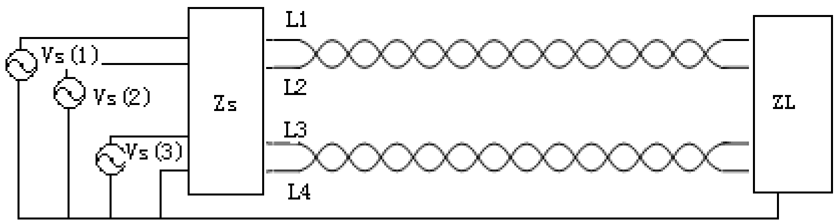
Both multi-pair bonding and MIMO DSL are signal transmission technologies using multiple twisted pairs. Two twisted pairs are used as an example. In this example, four physical copper lines are respectively referred to as L1, L2, L3, and L4 as shown in Figure 2-1.

Figure 2-1 Channels constructed by two twisted pairs



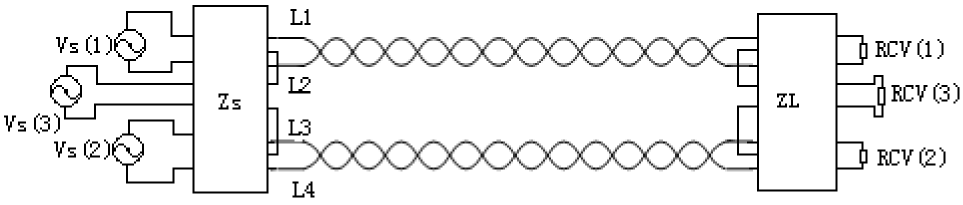
According to the signal transmission theory, any two of the four lines can form a current loop to transmit signals. (L1 and L2) and (L3 and L4) can form two transmission loops, which is the mode that telephones and DSL commonly use. More loops can be formed, but not all loops can be used to transmit signals simultaneously. According to the Kirchhoff's voltage law, only three loops among all possible loops are independent of each other and thus can be used to transmit three independent signals. The preceding two twisted pairs are still used as an example. (L1, L4), (L2, L4), and (L3, L4) that are independent of each other, and can be used to transmit 3 independent signals. This is the split-pair technology introduced by Bin Lee, John M. Cioffi, and others in *Binder MIMO channels Communications* in 2004. The split-pair technology constructs 2N-1 channels in 2N lines, leading to the possibility of achieving 1Gbps with four pair cables [2].

Figure 2-2 Gbps DSL model realized by the split-pair technology[2]



Not all loops that are independent of each other can be practically used to transmit signals in any scenarios. Whether a loop can be used to transmit signals depends on actual scenarios. For example, among the loops (L1, L2), (L3, L4), and (L2, L3), L2 and L3 are not twisted together, which may result in high egress and poor immune to ingress interference. To solve this problem, in one example, L1 transmits the same signal as L2 and L4 transmits of the same signal as L3. In this way, due to characteristics of twisted pairs, a part of egress signals is canceled and the anti-interference performance is enhanced. This is the phantom mode [1] previously put forward in the industry.

Figure 2-3 Phantom mode[1]



There are N (2N-1) combinations if two lines among 2N lines form a combination. If we also consider choosing more than 2 lines out of 2N lines, there are more combinations. How to select out (2N – 1) optimal independent combinations should be carefully studied. Randomly combined lines without considering the native combinations cannot make full use of the advantage of twisted pair cable structure. Keeping the channels of the N twisted pairs (hereinafter referred to as the native channels) and expanding another N–1 channels (hereinafter referred to as the virtual channels) result in better performance. Two twisted pairs are used as an example to show how SuperMIMO channels are constructed as shown in Figure 2-4 and Figure 2-5.The SuperMIMO channels are constructed in alternative mode (AM) and common mode (CM) according to different combination modes and the characteristics of signal transmission. Vs (1) and Vs (2) use native channel while Vs (3) takes advantage of the constructed virtual channel.

Figure 2-4 Channels constructed in AM

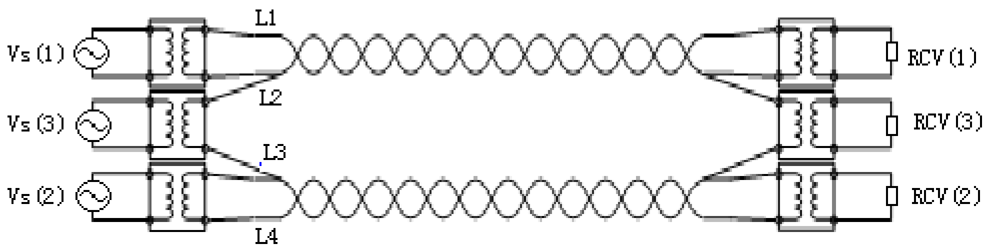
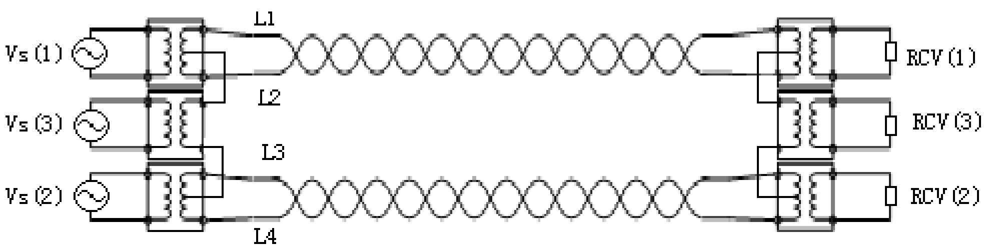


Figure 2-5 Channels constructed in CM



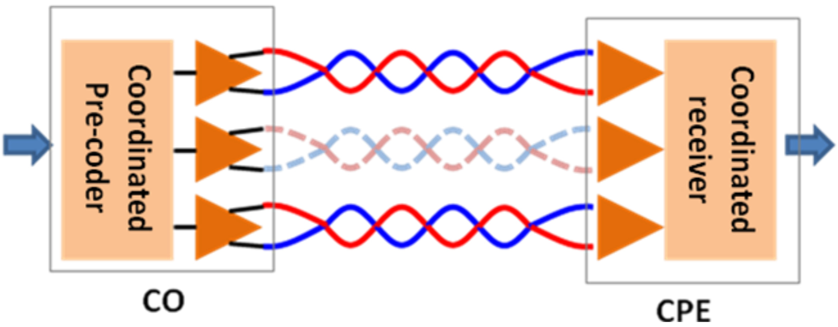
Furthermore， we generalized the AM and CM mode to application of superMIMO with more than two pairs. The generalized mode of AM and CM eliminates the shortcoming of split pair in figure2, which uses one line for return path of all channels and may cause strong coupling between channels; gets better consistency between the virtual channels; and makes it easier to implement.

2. Cancel crosstalk between channels by using the crosstalk cancellation technology.

Crosstalk also exists among SuperMIMO channels. The crosstalk includes not only inherent crosstalk due to electromagnetic coupling but also crosstalk due to different combinations that SuperMIMO uses. The measurement result of the SuperMIMO channel matrix indicates that direct attenuation on the virtual channels is similar to that on the native channels, but crosstalk between a virtual channel and a native channel is often far greater than that between native channels. In some frequency bands, the amplitude of crosstalk transfer function may be even greater than that of native channel transfer function. The crosstalk may cause severe degradation on SuperMIMO performance if it is not cancelled properly. The laboratory test results show that, in some cases, the total rate of the SuperMIMO twisted pairs may be even lower than that of regular twisted pairs if crosstalk cancellation technology is not used. Therefore, typically, the potential of SuperMIMO can be brought into full play only if the crosstalk cancellation technology is used.

Because crosstalk amplitude between virtual channels may be even greater than that of native signals, commonly used simple vectoring techniques may not cancel crosstalk to a satisfactory level. Coordinated processing at both ends is an effective method to improve crosstalk cancellation performance. Namely, for signals in one direction, the signals are pre-coded at the transmit end and jointly received at the receive end, as shown in Figure 2-6.

Figure 2-6 Coordinated processing at both ends



Crosstalk cancellation by coordinated processing at both ends can not only eliminate crosstalk among independent lines of SuperMIMO but also make elimination of some external spatially correlated noises possible.

Although implementation of crosstalk cancellation by coordinated processing at both ends is complex, crosstalk cancellation performance is dramatically improved and thus the total rate is increased. As a result, SuperMIMO is more effective to a variety of lines and scenarios

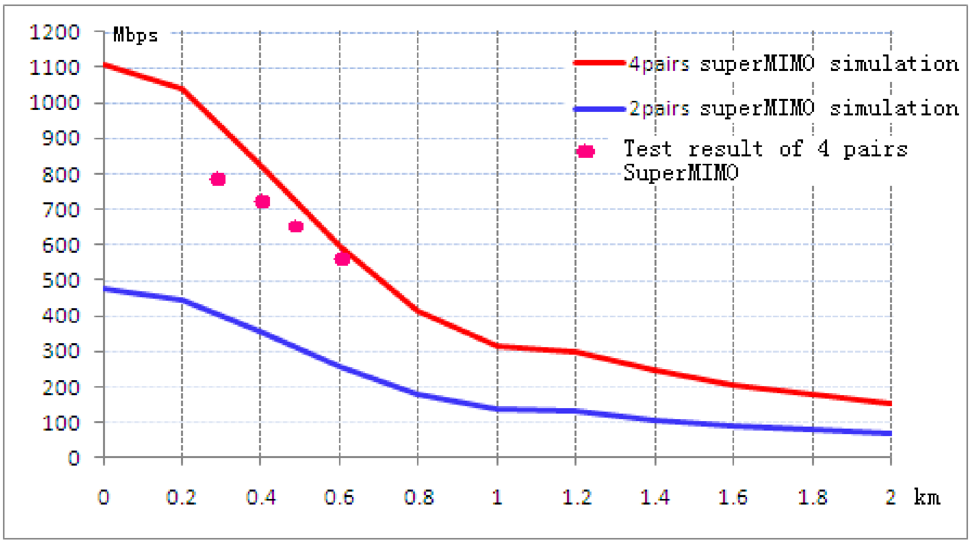
3. Use multi-pair bonding to increase the rate

SuperMIMO uses multi-pair bonding technology that aggregates signals in different channels, together with its channel expansion and crosstalk cancellation technology, to provide higher rate than MIMO DSL.

2.3 Performance of SuperMIMO

SuperMIMO obtains gains by constructing extra virtual channels to transmit signals and canceling crosstalk among channels by using the crosstalk cancellation technology. Therefore, SuperMIMO can obtain additional gain of N–1/N compared with MIMO DSL (N is the number of the native channels, that is, the number of twisted pairs). The simulation results in Figure 2-7 shows attainable rate of two pairs (N=2) and four pairs (N=4) SuperMIMO simulation result. For comparison, some test result over real cable was also illustrated. Due to the implementation loss, overhead and bit loading cap (maximum bit loading per subcarrier no more than 15bits), the test results are usually below the attainable rate.

Figure 2-7 Performance of SuperMIMO



Test data from the prototype based on VDSL2 17a bandplan proves the preceding analysis and simulation results. Figure 2-8 and Figure 2-9 provide test data of the prototype and the demonstration environment.

Figure 2-8 Test data of SuperMIMO performance

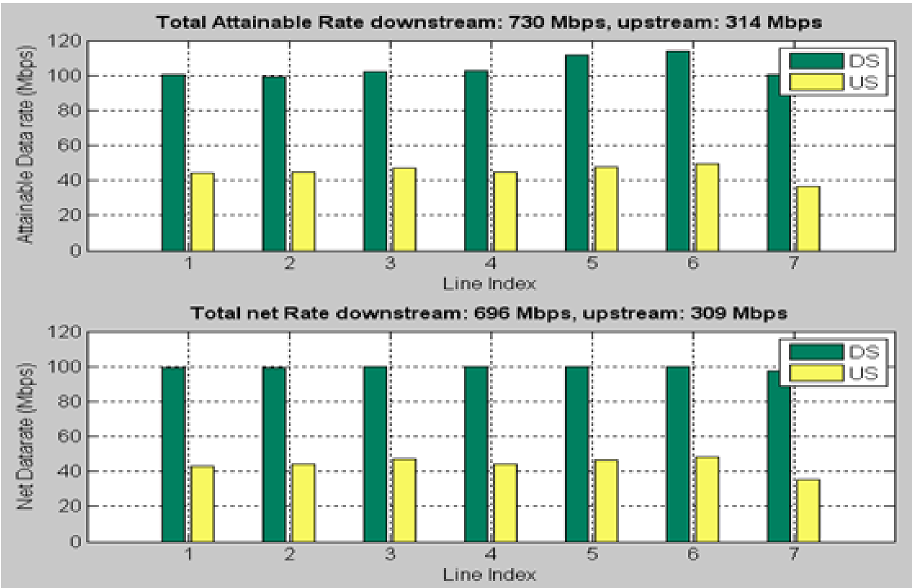
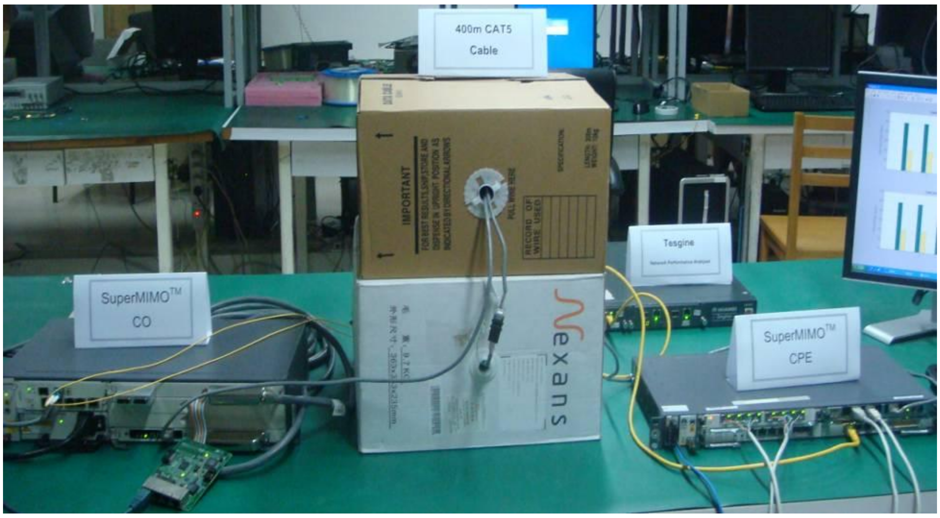


Figure 2-9 Test configuration for the SuperMIMO prototype



2.4 Technical Challenges SuperMIMO Faces

1. Characteristic impedance

Characteristic impedance of a native twisted pair is usually designed to be about 100 ohms. According to the transmission line theory, whether the impedance of the analog front-end circuit and the line matches directly affects the quality of signal transmission. If impedance of the front circuit and the line does not match well, the signal-to-noise ratio (SNR) of received signals is degraded. Therefore, the characteristic impedance of virtual pairs in SuperMIMO should be carefully studied.

However, to perform quantitative analysis to the characteristic impedance of the virtual pairs is impossible because spacing between randomly selected pairs and parameters about the twisted pairs are unobtainable and loop resistance of a line changes in CM (spacing between pairs, parameters about the twisted pairs, and the loop resistance are main factors in determining the characteristic impedance of a line). As for SuperMIMO, there are several virtual pairs. Consequently, it is hard to make quantitative analysis to the characteristic impedance. According to statistics analysis based on measurement result on 25-binder in laboratory, impedance of virtual channels ranges from 90 ohms to 120 ohms, which fall in the range of nominal values of DSL hybrid circuit impedance. To optimize the SuperMIMO performance, hybrid circuits can be designed to work in adaptive mode in which the impedance is adjustable within a certain range. In this way, the matching problem between the hybrid circuit and the non-twisted lines can be solved.

2. Ingress and egress related to virtual channels

Because virtual channels are not regular twisted pair channels, the longitudinal balance loss may be pretty low. Consequently, virtual channels are poor at suppressing the ingress and egress compared with the native twisted pair channels. Therefore, even though both total transmitting power and power spectral density (PSD) meet DSL standards, interference to other users and radiation produced by SuperMIMO may exceed the range allowed. In local loop unbundling (LLU) scenarios, interference from SuperMIMO group to lines of other operators should be carefully studied.

In addition, the virtual pair channels are more sensitive to alien interference and interference from adjacent channels than the native twisted pair channels. Therefore, virtual pair channels may be severely interfered by others in one cable. Alien crosstalk cancellation is a possible solution to the preceding problem.

3. Engineering application of SuperMIMO

Similar to Vectored DSL, the mapping relationship between twisted pairs and DSL ports are scrambled by the main distribution frame (MDF). If lines in a SuperMIMO are in different binders, the generated virtual channel then crosses different binders. In this case, the virtual channel is more prone to interference and performance may become worse. Therefore, the features of virtual channel generated cross different binder should be further studied.

4. Equipment interconnection

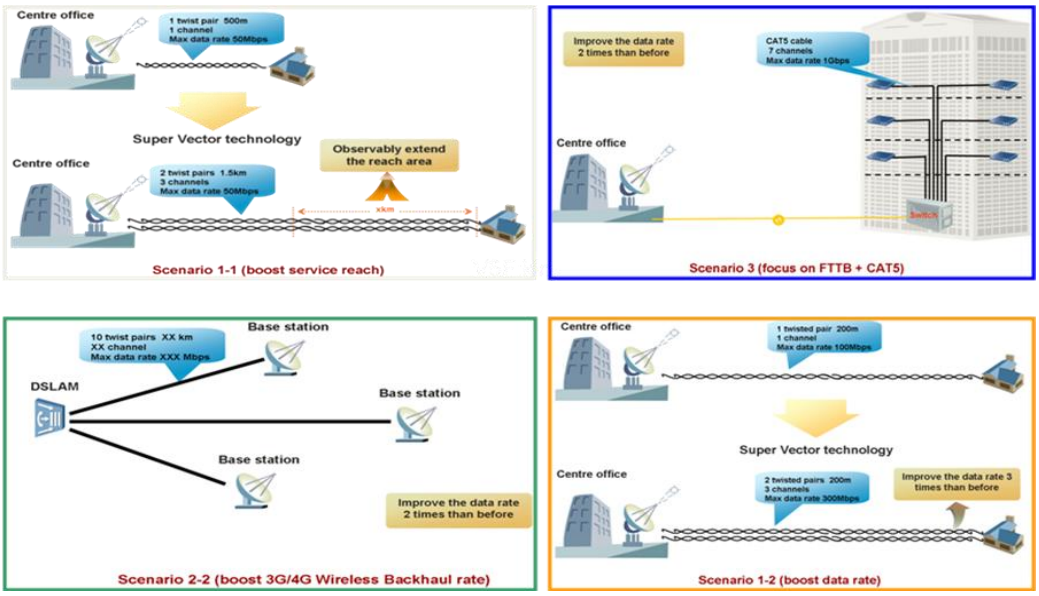
Widely-accepted standards should be established for SuperMIMO so that equipment of different vendors can interoperate with each other. Multi-pair bonding and crosstalk cancellation have already been standardized by ITU-T. Operators and equipment vendors should make joint efforts to establish standards for SuperMIMO channels.

3 Application and Prospect of SuperMIMO

3.1 Major Application Scenarios of SuperMIMO

SuperMIMO can be used in scenarios where DSL bonding is applicable and can dramatically increase access bandwidth and/or extend transmission range. Meanwhile, SuperMIMO can meet requirements for higher bandwidth in the future and be used for small-scale base stations/femtocell and DSLAM backhaul. Therefore, SuperMIMO can be a substitute of optical backhaul, especially in areas where optical fibers are unavailable. When SuperMIMO is used for base station backhaul, time synchronization may be needed. ToD over DSL submitted to the ITU-T by Huawei is expected to be approved in early 2011. SuperMIMO may be applicable in the following scenarios.

Figure 3-1 Application scenarios of SuperMIMO



3.1.1 SuperMIMO for Long Distance

When SuperMIMO is used for backhaul, lines may be quite long, e.g., over 2 km. At such a long distance, gains due to crosstalk cancellation are limited because crosstalk on native channels is attenuated on the line. In this case, crosstalk cancellation may not be needed.

However, the crosstalk caused by the virtual channels may be higher, so the crosstalk cancellation may still provide some gains. Nevertheless, SuperMIMO may still provide higher access bandwidth than bonding even if crosstalk cancellation is not used.

When SuperMIMO is applied on long loops, since crosstalk cancellation may not be used. If other DSL lines coexist, the following requirements should be met: 1) The crosstalk between virtual channels should not be too high; 2) The crosstalk between SuperMIMO virtual channels and the native channels should not be too high. Test results show that not all SuperMIMO modes meet the preceding requirements. In current technologies, it appears that two twisted pairs in CM meet the preceding requirements. When SuperMIMO is used for point-to-point applications (such as base station or DSLAM backhaul), and no other services are in the same binder, the preceding requirements may be relaxed.

That is, if SuperMIMO is used in a long distance and other DSL lines coexist, two twisted pairs in CM are more suitable. In that case, SuperMIMO in this scenario can provide a rate three times as much as one twisted pair DSL.

3.1.2 SuperMIMO for Short Distance

Usually, there are redundant lines between the drop point and a subscriber’s premise. In North America and most area of Europe, two twisted pairs connect to a subscriber's house; in China, four pairs connect to a subscriber's house. Therefore, SuperMIMO applicable in FTTC/B scenario can provide a maximum access rate of 300 Mbps using 2 pairs or 700 Mbps using 4 pairs. When the access distance is within 1 km, crosstalk between channels significantly degrades the line transmission performance， thus it is necessary to adopt the crosstalk cancellation technology to cancel crosstalk for providing higher access rate. Therefore, if SuperMIMO is used for short distance, crosstalk cancellation is usually required. SuperMIMO ports can be integrated on a Vectoring subscriber board. In this way, use of SuperMIMO or Vectoring depends on subscriber's demand, which facilitates management and maintenance of equipment.

3.2 Prospect of SuperMIMO Applications

As ADSL providing a bandwidth of 6 Mbps, ADSL2+ 25 Mbps, VDSL 52 Mbps, and VDSL2 symmetric 100 Mbps, access over twisted pair keeps developing to meet requirements for higher bandwidth. SuperMIMO helps further tap into the bandwidth potential of twisted pairs and data from simulation and prototype tests shows the great capability of twisted pairs. SuperMIMO can help to prolong the life cycle of twisted pairs.

Huawei, a mainstream DSLAM vendor, announced a SuperMIMO prototype with a 700 Mbps rate over 400 meter cable in Hong Kong in September 2010. In April 2010, Bell labs of Alcatel-Lucent announced that its simulation of DSL phantom mode using two twisted pairs (0.6mm diameter of copper line) has boosted the rate to 300 Mbps. It is expected that other vendors will soon join the research and development effort on this technology.

So far, SuperMIMO is realized only on the prototype. SuperMIMO still faces many challenges, before its large-scale deployment on the real network. In addition, it is essential for equipment vendors in the industry to make joint efforts to work out corresponding standards for interoperability between equipment from different vendors. The progresses made by leading DSL vendors such as Huawei, and Alcatel-Lucent will certainly push forward the standardization of this promising technology.

4 References

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